LONGITUDINAL PHENOMENA DURING THE LHC CYCLE

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Abstract

At the moment longitudinal beam parameters in the LHC are fixed at the lowest and highest energies [1]. During the cycle they can be found from beam stability conditions. This also allows us to define requirements for HOM damping. The necessity of continuous emittance increase on the ramp is shown and different scenarios of controlled blow-up are presented. Possible reasons for particle loss at the beginning of acceleration and later, during the ramp, are discussed.

1 GENERAL CONSIDERATIONS

We start from a general consideration of the possible different accelerating cycles in the LHC.

For a given magnetic cycle, [2], the voltage programme for a single harmonic RF system is fixed by the longitudinal beam emittance ε and filling factor q.

At injection into the LHC the emittance will be in the range from 0.5 to 1 eVs depending on how well intensity effects can be controlled in the SPS, since the nominal emittance at injection to the SPS is 0.35 eVs, [3].

To have a clean bunch into bucket SPS-LHC transfer for emittances higher than 0.5 eVs, a 200 MHz RF system was proposed, to be used only for capture, in addition to the main 400 MHz RF system, [4]. For capture the operational total voltage at 200 MHz is 3 MV [5]. In the present scenario after capture the voltage of the 400 MHz RF system is adiabatically increased up to 8 MV and the voltage of the 200 MHz RF system is decreased to zero.

On the flat top the emittance is required to be 2.5 eVs [1]. To have the shortest possible bunch length during collision the maximum available voltage (16 MV) at 400 MHz will be applied producing $\sim$1 ns long bunches.

These boundary conditions leave at first view some freedom for the choice of parameters during the ramp. First of all, there are the restrictions for different possible scenarios due to the maximum available voltage. In Fig. 1 voltage programmes calculated both for the 200 MHz and 400 MHz RF systems used separately as a single RF system are presented for different emittances in the range from 0.5 to 2.5 eVs and fixed filling factor in momentum $q_p = 0.9$. Note, that these voltage programmes do not satisfy the "boundary conditions" at the flat bottom and flat top.

The 200 MHz RF system with 3 MV available can be used for acceleration of bunches with emittance ≤ 2.0 eVs from the beginning of the cycle. This could be an interesting option for the beginning of LHC commissioning with acceleration since it allows losses to be avoided during transfer to the 400 MHz RF system for large emittances.

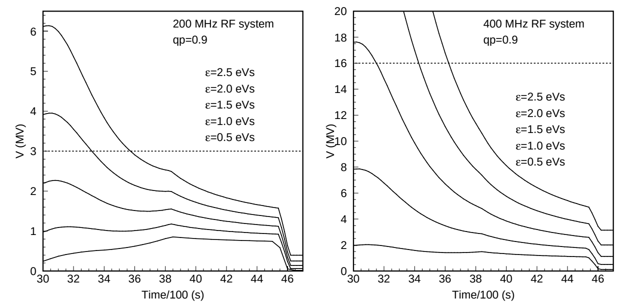

Figure 1: Voltage programme with fixed filling factor $q_p = 0.9$ for single 200 MHz (left) and 400 MHz (right) RF systems for different (constant) values of longitudinal emittance. Dashed line indicates hardware limit for voltage amplitude.

No longitudinal feed-back system is forseen for the LHC [6]. The main argument for this decision is that from the hardware point of view it is difficult to do better than the natural Landau damping due to synchrotron frequency spread. As a result we rely on

- being below the thresholds of coupled bunch instabilities due to narrow-band impedances,
- not losing Landau damping due to broad-band impedance.

The beam stability issues are considered in the next section. For more details see [7].

2 BEAM STABILITY

2.1 Narrow-band impedance

For equally spaced bunches the thresholds for coupled-bunch instability due to a narrow-band resonant impedance with frequency f_r calculated during the cycle, are shown in Fig. 2 for emittances of 0.5 eVs and 1 eVs and a voltage of 8 MV (left). They are found for the resonant impedance frequency $f_r = f_r^{min}$ which corresponds to the worst case.

As one can see from Fig. 2, for a fixed emittance and voltage, the threshold shunt impedance decreases towards the end of the cycle. For the worst-case frequency $f_r^{min} \simeq 0.43/\tau$, it scales with energy E as [7]

$$R_{sh}^{thr} \propto \frac{\varepsilon^2 h^2}{E\tau} \propto \frac{\varepsilon^{3/2} V^{1/4} h^{9/4}}{E^{3/4}}, \qquad (1)$$

where τ is the bunch length and h is the harmonic number (in the LHC for the 400 MHz RF system $h = 35640$).

Since at injection the emittance will be less than 1.0 eVs it should be increased in a controlled way at some moment

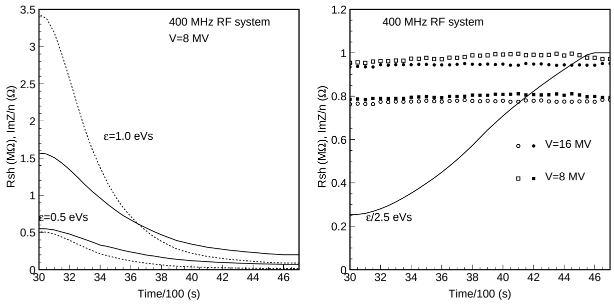

Figure 2: Left: Narrow-band (solid line) and broad band (dashed line) impedance threshold during the cycle for emittances of 0.5 eVs, 1 eVs and voltage of 8 MV in 400 MHz RF system. Right: Narrow-band (filled symbols) and broad-band (empty symbols) impedance threshold for emittance change according to (3) - solid line and constant voltages of 8 MV (squares) and 16 MV (circles). Thresholds correspond to nominal beam current $I_0 = 0.56$ A and bunch current $I_b = 0.2$ mA.

in the cycle to have 2.5 eVs at the flat top. This can be done neither on the flat bottom nor too early during the cycle due to the voltage being limited to 16 MV, see Fig.1 (right).

It follows from Eq.(1) that to avoid decreasing the threshold during the cycle the emittance should be increased with energy not slower than

$$\varepsilon \propto E^{1/2}/V^{1/6}. \tag{2}$$

Note, that the bucket area also grows with energy as $E^{1/2}$. For 8 MV voltage at 450 GeV and 16 MV at 7 TeV in the 400 MHz RF system, we find from this scaling law that the emittance at the beginning of the ramp should not be less than 0.7 eVs.

In Fig.2 (right) the threshold impedance corresponding to an emittance change

$$\varepsilon(E) = \varepsilon_{max}(E/E_{max})^{1/2} \tag{3}$$

is shown for a constant voltage of 8 MV and 16 MV. Then for ε_{max} = 2.5 eVs the initial emittance ε(0.45 TeV) = 0.63 eVs.

2.2 Broad-band impedance

The stability criterion for narrow-band impedances analysed in the previous section, is derived ignoring the presence of any other impedance in the ring and assuming that there is Landau damping. This condition is not satisfied if the coherent frequency shift of the given azimuthal mode m due to the broad-band impedance is larger than one fourth of the synchrotron frequency spread [8]. The preservation of natural Landau damping is especially important in the absence of a longitudinal feedback system [6].

During the cycle the threshold changes as

$$\mathrm{Im}Z^{thr}/n \propto \frac{\varepsilon^2 \tau h^2}{E} \propto \frac{\varepsilon^{5/2} h^{7/4}}{E^{5/4} V^{1/4}}. \tag{4}$$

For a constant emittance the threshold quickly drops down with energy, as can be seen in Fig. 2 (left).

Neglecting the weak dependence on voltage amplitude, we find from (4) that the condition to avoid decrease of the threshold (4) during the cycle,

$$\varepsilon \propto E^{1/2} V^{1/10}, \tag{5}$$

is similar (but slightly less strong) to the one found above for the narrow-band impedance, see (2).

The threshold for the imaginary part of the broad-band impedance with a change of emittance during the cycle $\propto \sqrt{E}$ is shown in Fig. 2 (right) for constant voltages of 8 MV and 16 MV.

Even for ultimate bunch intensity ($I_b = 0.3$ mA) the minimum threshold value during the cycle $0.5\ \Omega$ is well above the present estimation of the inductive part of the LHC broad-band impedance, [9], [6], which is $\mathrm{Im}Z/n \simeq 0.15\ \Omega$.

Additional margins may come from the fact that in this consideration the effect of incoherent frequency spread was not taken into account.

However as we will see below the most critical area is, in fact, beam stability at injection.

2.3 Beam stability on the flat bottom

The present scenario for injection into the LHC is the following [5]:

- capture in the 200 MHz RF system with 3 MV voltage; during this period the 400 MHz RF system is used for wave-form linearization with 0.75 MV;
- adiabatic bunch transfer from 200 MHz to 400 MHz by increasing the voltage in the 400 MHz RF system up to 8 MV and decreasing the voltage in the 200 MHz system to zero;
- start of acceleration with the 400 MHz alone, the 200 MHz being actively or passively damped.

Let us consider first the beam stability in the 200 MHz RF system alone. Assuming matched conditions, we obtain the limitations shown in Fig. 3 as a function of emittance.

For the same emittance the thresholds in the 200 MHz RF system are lower than in the 400 MHz due to decreased nonlinearity and therefore synchrotron frequency spread (proportional to h^2), see (1) and (4). However one should take into account that the lower harmonic, 200 MHz RF system, allows capture without losses of emittances at least twice higher than the 400 MHz RF system (bucket area is proportional to $h^{-3/2}$). Then the stability conditions in the two RF systems are comparable.

The limitation for broad-band impedance at injection is the same as at 7 TeV with 2.5 eVs emittance only for emittances around 0.9 eVs. For low emittances (0.5 - 0.6 eVs) the risk of losing Landau damping due to the broad-band impedance becomes significant. To improve the situation

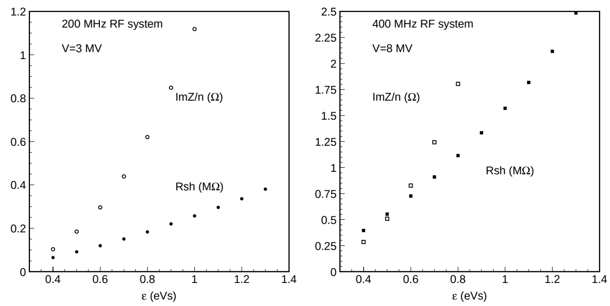

Figure 3: Narrow-band and broad-band impedance threshold at 450 GeV as a function of emittance in 200 MHz, 3 MV (left) and 400 MHz, 8 MV (right) RF systems. Thresholds correspond to nominal beam and bunch current, $I_0 = 0.56$ A and $I_b = 0.2$ mA.

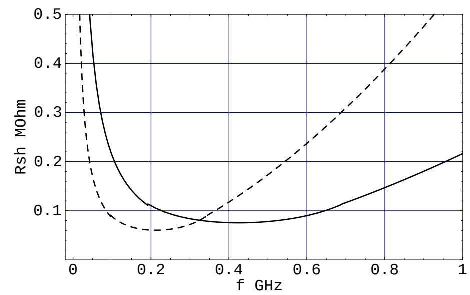

Figure 4: Limitation on shunt impedance of narrow-band resonances as a function of their frequency for an emittance of 0.7 eVs at 450 GeV in 200 MHz RF system with 3 MV for two different particle distributions (a = 1 - dashed curve and a = 0.25 - solid curve). Thresholds correspond to nominal beam current $I_0 = 0.56$ A.

some emittance blow-up can be performed, if necessary, either in the SPS or in the LHC. In the last case this can be due to filamentation of an unmatched bunch or be done artificially after capture, for each batch separately.

For emittances around 1 eVs it is foreseen to use the 400 MHz RF system for wave-form linearization which should decrease filamentation and provide a better capture into the 200 MHz RF system. In this case one can expect a decrease in the thresholds of around 10% in comparison with the limitations presented in Fig. 3 (left). For lower emittances wave-form linearization is less necessary and therefore the 400 MHz RF system can be used to increase Landau damping - in bunch lengthening or bunch shortening mode.

2.4 *Requirements for HOM damping*

The criterion for coupled bunch instability derived for equally spaced bunches was applied above, using the nominal average beam current, for an LHC beam which in fact consists of many batches and gaps. For lowest-limit estimation of thresholds one should therefore introduce a factor of $M * 10/h \simeq 0.8$ (M is the number of bunches in the ring). Another change can come from considering different types of particle distribution. As was mentioned above using linearization of the wave-form at injection for large emittances also brings the narrow-band impedance threshold down by factor 0.9. Finally we also introduce a safety factor 1/2.

The limiting curves in Fig. 4 for two different types of particle distribution (a = 1 and a = 0.25, see [10]) and 0.7 eVs emittance in 200 MHz with 3 MV can be considered then as the requirement for HOM damping.

To be safe for the nominal intensity for emittances starting from 0.7 eVs and for ultimate intensity for an emittance of 1.0 eVs, one should limit the shunt impedance to 60 kΩ in the frequency range (100 - 500) MHz. The limitation for R_{sh} then increases with frequency as $f_r^{5/3}$.

3 THE "OPTIMUM CYCLE"

3.1 *Beam parameters*

For voltage changing between 8 and 16 MV according to the formula, (Fig. 5, left)

$$V = 16\,(E/E_{max})^{1/4}\ [\mathrm{MV}], \qquad (6)$$

we obtain from (2) the required emittance blow-up law (Fig. 5, right)

$$\varepsilon = \varepsilon_{max}(E/E_{max})^{11/24}, \qquad (7)$$

which in practice is not very different from (3).

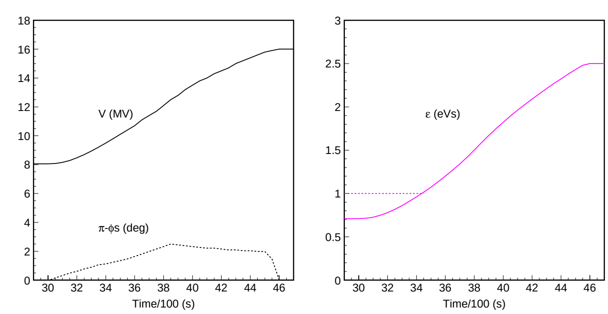

Figure 5: Voltage, synchronous phase in degrees at 400 MHz (left), and emittance (right) during the cycle.

This acceleration cycle provides

- the required bunch parameters at flat bottom and flat top;
- constant stability conditions during acceleration for the narrow-band impedance and no degradation for the broad-band impedance, with minimum controlled emittance blow-up;

- a small filling factor during the ramp to ensure emittance blow-up without losses.

3.2 Emittance blow-up

If at the beginning of the ramp the emittance is more than 0.7 eVs, the beam should be blown up only from the point where the emittance becomes less than the emittance from the blow-up curve in Fig. 5 (right).

Controlled emittance blow-up can be achieved using

- phase or amplitude modulation at high harmonic RF frequency as is operational in the CERN PS (from 1975), PS Booster, SPS (MDs), AGS. The experience shows that harmonic ratio should be h2/h1 $\geq$ 4 which implies an additional 1.6 GHz RF system in the LHC.

- band-limited (pink) noise introduced through the phase or amplitude loop as was done during $p\bar{p}$ operation in the SPS [11] and more recently in the KEK PS [12]. For the excitation at the quadrupole synchrotron frequency: $\omega_{noise} \simeq 2\omega_s$.

To minimize particle losses, emittance blow-up should be performed for a bunch with weak nonlinearity (no excitation at higher frequencies) and having enough free space in the bucket.

The variation of the synchrotron frequency spread during the acceleration cycle is shown in Fig. 6 (left) together with the energy spread. As one can see the relative synchrotron frequency spread is always below 0.2. The minimum width of the spectrum in frequency is only a few Hz. The synchrotron frequency f_s during the cycle is shown in Fig. 6 (right).

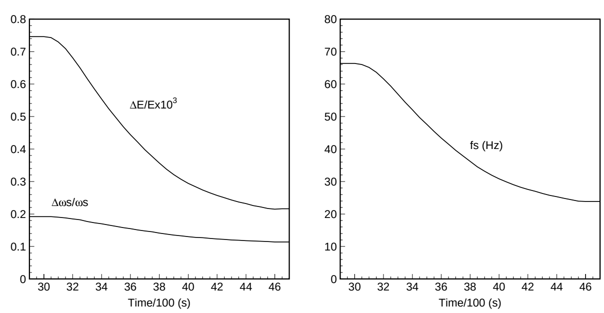

Figure 6: Relative energy and synchrotron frequency spread (left) together with synchrotron frequency f_s (right) corresponding to voltage programme and emittance change shown in Fig.5.

These voltage and emittance programmes, do not give any increase in energy spread at the beginning of the ramp.

The corresponding bunch length and filling factor are shown in Fig.7 (left). For this voltage programme the bunch does not occupy more than 60% of the bucket area.

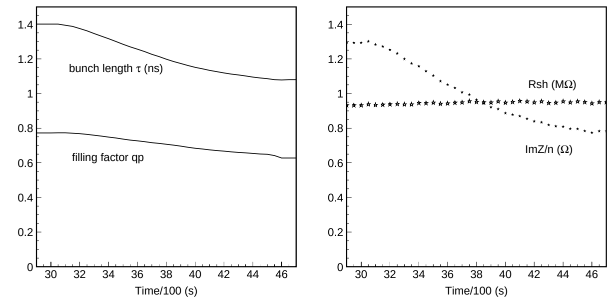

Figure 7: Bunch length and RF bucket filling factor in momentum (left) corresponding to voltage and emittance programmes shown in Fig. 5 together with narrow-band and broad-band impedance threshold (right).

3.3 Beam stability

The voltage and emittance programmes from Fig. 5 provide threshold impedances for R_{sh}^{min} (minimum value at $f_r = f_r^{min}$) and $\mathrm{Im}Z/n$ as shown in Fig. 7. As expected there is no degradation of thresholds during the cycle compared to the fixed value on the flat top.

Even with the threshold impedances R_{sh}^{min} and $\mathrm{Im}Z/n$ at injection being below those on the flat top (for 2.5 eVs bunches), emittance blow-up might be still necessary during the cycle. Indeed, for narrow-band impedances for resonant frequencies above 400 MHz, R_{sh}^{thr} is decreasing as the bunch shrinks from (2 - 2.5) ns at injection to $\leq$ 1 ns on the flat top. Values of R_{sh}^{thr} as a function of resonant frequency for 0.5 eVs and 1 eVs emittances in 200 MHz RF system at injection are shown in Fig. 8 together with the limitation on the flat top for 2.5 eVs bunches in 400 MHz RF system. As one can see, for high resonant frequencies the limitation on the flat top for 2.5 eVs emittance is below that on the flat bottom for initial emittances around or more than 1 eVs due to bunch length variation.

Without emittance blow-up the limitation for $\mathrm{Im}Z/n$ during the cycle, see Fig. 2, also quickly drops down below its injection level in Fig. 3.

4 PARTICLE LOSS

For the LHC as a superconducting machine it is extremely important to keep particle loss below the allowed limit. Possible sources of particle loss coming from longitudinal plane during injection and acceleration are

- capture into the 200 MHz RF system;
- transfer to the 400 MHz RF system;
- RF noise (see results of MDs in the SPS in 2000);
- bunch excitation by pink noise for controlled emittance blow-up with possible variation of emittance from bunch to bunch and from batch to batch (discussed also at MAC, November 2000);

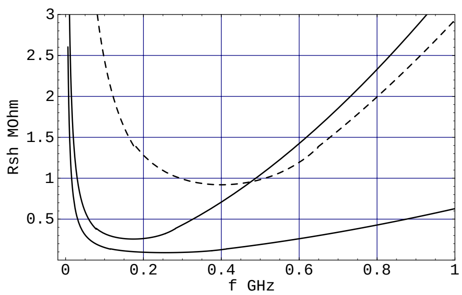

Figure 8: Limitation on shunt impedance of narrow-band resonances as a function of their frequency for emittances of 0.5 eVs (lowest curve) and 1 eVs in 200 MHz RF system (with 3 MV) at 450 GeV together with the limitation for 2.5 eVs bunches in 400 MHz RF system (with 16 MV) at 7 TeV (dashed curve). Thresholds correspond to nominal beam current $I_0 = 0.56$ A.

- beam instabilities

The first three items will give detectable loss at the beginning of ramp. Apart from the damping system already forseen at injection, [13], cures for these particle losses could be:

- small emittances at injection;
- low-noise electronics in the RF systems;
- weak nonlinearity (small synchroton frequency spread);
- possibility to blow-up emittance of each batch separately;
- control of impedance, both narrow-band and broadband;
- longitudinal feedback system if it proves necessary.

In all cases good diagnostics to accurately measure the bunch length of each bunch is imperative.

5 SUMMARY

- For the LHC acceleration cycle, voltage and longitudinal emittance blow-up programmes are suggested which satisfy boundary conditions and provide the required beam stability.
- For an initial emittance of 0.7 eVs a controlled emittance blow-up proportional to $\sqrt{E}$ is sufficient to avoid degradation of stability during the ramp (compared to the fixed value on the flat top).
- With this emittance blow-up during the cycle the most critical area for beam stability is the flat bottom.
- To minimize particle loss during capture and transfer from the 200 MHz to 400 MHz RF system emittances as small as possible are desirable. However emittances below 0.7 eVs are not acceptable from the stability point of view.
- The requirement to damp HOM to below 60 kΩ (in frequency range 100 - 500 MHz) should permit injected emittances of (0.7 - 1) eVs for nominal beam intensity and $\sim$1 eVs for ultimate.
- Emittance blow-up using pink noise should be studied in more detail (MDs in the SPS).

6 ACKNOWLEDGMENTS

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